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Space Shuttle Fatigue Loads Spectra for Prelaunch and Liftoff Loads*

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Judith Goldish
Rockwell Space Systems Division
Downey, CA

Raphael Ortasse **
Rockwell Space Systems Division
Downey, CA

SUMMARY

Fatigue loads spectra for the prelaunch and liftoff flight segments of the Space Shuttle were developed. A variety of methods were used to determine the distributions of several important parameters, such as time of exposure on the launch pad, month of launch, and wind speed. Also, some lessons learned that would be applicable to development of fatigue loads spectra for other reusable space vehicles are presented.

INTRODUCTION

Fatigue loads spectra for the shuttle.

The mission profiles for the Space Shuttle are unique because it is the only reusable space vehicle being flown today. This paper presents a discussion of the development of mission profiles for the prelaunch and liftoff flight segments of the space shuttle mission. The prelaunch and liftoff segments are not similar to anything experienced by a conventional aircraft. The methods developed for them may be useful examples for other programs.

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** Team lead engineer. Other team members included: Richard L. Stauf, Saroj Gupta, Brent A. Mann, Daniel D. Paul, Lawrence V. Purtle, William Harvey. Also Lawrence Tischner, Rudy Loera, Wendy W. Chang, Ramon C. Perez, Arthur Leong, Anne Armstrong, Scott Foust, Walter Miller, Lavant Wooten, and others.

For both prelaunch and liftoff, the starting point for the fatigue loads method was the methods already being used for development of design loads. In both cases, the tools for the design method were already in place, well designed, mature, and flexible. Even so, a considerable amount of effort was needed to adapt these tools for use in developing fatigue loads. Some reasons why this effort was needed are:

- Fatigue requires a time history of the loads where design requires only the single maximum load.

- In development of design loads generally every load case is desired to be a "worst" case. For fatigue, most cases should be "nominal" cases with only a certain number of occurrences of design type loads in the lifetime.

- The ground rules and assumptions for fatigue are different from those for design.

In the fatigue loads spectra process flow, Figure 1, the material covered in this paper falls within the first five steps.

The Space Shuttle

The Space Shuttle is designed to launch and retrieve a variety of payloads into and from earth orbit. The launch configuration consists of the Orbiter Vehicle, the External Tank (ET), and two solid rocket boosters (SRB). The Space Shuttle Vehicle is launched in a vertical attitude by means of the Space Shuttle Main Engines (SSME's) and two SRB's. The orbiter lands horizontally, similar to conventional aircraft. Figure 2 shows the configuration of the Space Shuttle. Figure 3 depicts a typical Shuttle mission. Prelaunch and liftoff, which are discussed in this paper, are shown in the lower left of the figure.

Fatigue generally requires looking at the entire vehicle mission including all flight segments because different components and parts are critically loaded in different flight segments.

PRELAUNCH

The Prelaunch Flight Segment

Prelaunch is the period from arrival of the Space Shuttle on the launch pad to main engine ignition. The main sources of loads are gravity, wind, and the Space Shuttle Main Engines (SSME's). Gravity itself is not cyclic in nature, but the movement of the structure due to wind loads causes the center of gravity to shift and causes freeplay in the joints between the components, and these effects do cause cyclic type loading. However, both of these effects were already included in the computer program used for prelaunch analysis for design, so no additional effort was needed for fatigue.

The effect of wind loading on the Shuttle while on the launch pad is like a distributed load on a cantilever beam. On much of the structure the wind loads are not significant compared to loads during other flight segments. However, main engine thrust together with wind designs the aft skirt of the Solid Rocket Boosters (SRB's), the bolts that connect the SRB's to the Mobile Launch Platform (MLP), and the aft part of the SRB's.

For design loads, synthetic winds are used which are especially constructed to cause the greatest structural response. However, for fatigue, measured winds from Kennedy Space Center (KSC) were used. The issues that needed to be decided were: what winds to use, what the distribution should be (i.e.how many occurrences of the different wind speeds), and how long the total exposure time should be.

Time on the Launch Pad

The amount of time that the shuttle spends on the launch pad, exposed to wind, before launch affects the number of cycles of wind loading. The distribution of duration of stay on the launch pad is based on past experience. The past experience data do not fit any of the common distribution functions.

The time that the Shuttle has been exposed to the winds on the launch pad before a mission in the past has ranged from fourteen days to 161 days. The nominal time on the launch pad is 21 days currently, formerly 14 days. A launch delay and consequently longer stay may be caused by many types of weather problems, hardware problems, payload problems, conflicting launches from Cape Canaveral, etc. The maximum design case is a 180-day exposure, which by the ground rules was assumed to occur once in the fatigue lifetime. Inasmuch as neither the historic data for launch pad stay nor the factors that can affect it fit any of the common distribution functions, our approach to launch pad stay time was to use a probability of exceedance curve. The probability in the set of previous stays of exceeding each length of stay was plotted.

Table 1 shows the missions in the order that they were flown and the number of days the SSV was on the launch pad before the launch occurred. The average time on the launch pad for a mission was 42.0 days with a standard deviation of 31.2 days. Table 2 shows the months in which that stay occurred for each of the 41 launches.

Figure 4 shows the time on the launch pad for each mission in the order that they were flown. Neither a normal, polynomial, nor a Rayleigh distribution fits this data. A probability of exceedance method was used to derive the distribution of time on the launch pad. Figure 5 shows the probability of a stay on the launch pad exceeding a given length of time. This probability is derived from the 41 missions considered in the present analysis. In addition Figure 5 shows a line fitted through the measured data of the number of days stay on the launch pad. The line is the best fit to the log probability of exceedance that goes through the point giving 180 days a probability of 1 in 100 or 0.01, per a ground rule. Table 3 shows the probability of exceedance and the probability of a given stay on the launch pad from this curve, and Table 4 shows the number of missions in the 100-mission lifetime with each length of stay.

Month of Launch

The month of launch affects the winds encountered during liftoff and ascent. The missions are not evenly distributed among the months. Figure 6 presents the number and percent of all the 41 launches that occurred in each month of the year. We assumed, although no reason was known for the uneven distribution, that there were enough missions in the database that the distribution represented an actual bias, and therefore we distributed the month of launch according to the past missions rather than distributing them evenly between all the months. The distribution of month of launch that results from these numbers, though based on 41 actual missions and statistically projected to 100 missions, seemed biased for the months of April, September and November. At the direction of our customer, we revised the distribution on the following basis (see Figure 7):

1. The actual missions STS-1 through STS-40 as flown are used as the first 41 missions.

2. The three missions flown after STS-40 are used.

3. Forty-eight missions from the NASA flight manifest are used. (This manifest is a Flight Assignment Working Group's assessment of the NASA baseline for the future).

4. Eight missions are projected, based on (1) through (3).

The 180-day stay on the launch pad was placed to start in June, so that the stay on the launch pad will go through the months during which hurricanes are most likely to occur at Cape Canaveral. Furthermore, it was assumed that the Space Shuttle Vehicle is most likely to encounter a hurricane intensity wind during the 180-day stay on the launch pad.

After the length of stay on the launch pad and the month of launch for each mission were established, the 100 fatigue missions were sequenced in a random order.

Winds

For the fatigue loads spectra, measured winds were used. There was some difficulty in obtaining "nominal" wind data even though a large amount of wind data from Kennedy Space Center (KSC) is available. The distribution of the maximum hourly, daily, and monthly winds are available, but of course this cannot be converted into a forcing function. Also measured wind velocities and directions measured at 0.1-second intervals over time periods of about ten to twenty minutes in 1967-1968 were available for each month of the year, and these were used. These winds are somewhat conservative since the measuring instruments were especially likely to be turned on when a strong wind was expected. There is no way to know how the measured intervals differed from other intervals, or how typical the winds were in the years 1967-1968. Even if continuous long-term wind measurements had been available, they would probably have overstrained our computer resources at the time.

The computer program that calculates prelaunch loads, ASCENT, can handle forcing functions with up to 300 time points. Since the KSC winds were measured at a rate of one-tenth of a second, the winds were divided into segments of thirty seconds each. The segments were classified by the maximum wind speed in each segment. A Fast Fourier Transform was performed on each segment and the segment from each class with the most content at the first cantilever frequency of the Shuttle, 0.267 Hz, was selected. This resulted in the selection of a set of 30-second long wind segments. The ground rules called for one occurrence of a 47-knot wind and one occurrence of a 74-knot (hurricane speed) wind. A segment with a lower wind speed was scaled up to make these two segments.

The winds were taken from three directions, north, east, and south. (At that time it was believed that the launch tower effectively blocked winds from the west and therefore these could be ignored, so this was incorporated into the ground rules. Recent measurements during a storm showed that this may not be true in all cases.) The wind speed measurements in the segments were converted to Shuttle forcing functions.

The distribution of the wind segments versus wind speed was a Gumbel distribution with alpha=3.48 and gamma=7.42. This distribution was developed by NTI Corp. for NASA's Marshall Space Flight Center (MSFC). Note that the distribution is not dependent on the month in which the wind was originally measured or on the length of stay on the launch pad. Only the peak wind speed in the segment was considered in the distribution. The distribution of wind direction among the four cardinal directions was supplied by Marshall Space Flight Center as follows:

Direction	North (0°)	South (90°)	East (180°)	West (270°)
Wind speed:				(not used)
< 24 knots	24%	33%	25%	18%
≥ 24 knots	34%	22%	22%	22%

LIFTOFF

Liftoff Missions

Liftoff includes the ignition and buildup of the Space Shuttle Main Engines (SSME's), the ignition and buildup of the two Solid Rocket Boosters (SRB's), the breaking of the bolts that attach the SRB's to the Mobile Launch Platform (MLP), and the ascent of the Space Shuttle until it clears the launch tower.

The mission profiles for liftoff included:

- Nominal cases

- Design cases included in the ground rules:
  - Zero payload
  - Heavy payload (65,000 lb)
  - Engine out (one SSME shuts down after SRB ignition)(a design certification case)

- Design cases added to bring the set of fatigue loads close to the design certification set of 800 cases, identified by comparing body loads envelopes and attach loads:
  - Another engine-out on the other side of the Orbiter
  - Tuned gust winds instead of measured winds - one case for each cardinal direction, four altogether, to fill in SRB body loads envelopes. 34-knot tuned gust winds except South is 24-knots.
  - Seven cases to get design loads for the SRB and SRB/ET attach load indicators

- Non-flight conditions that are design certification conditions and hence were included in the ground rules:
  - One Flight Readiness Firing (FRF)
  - Two Pad Aborts (SSME's build up, then shut down)
  - (note: number of occurrences was established by the Loads and Dynamics Panel)

The system and method that were used for the design liftoff loads (DCR3) were also used for the fatigue loads. The existing cases could not be used because they were only run for ten seconds and we needed to run for fourteen seconds in order to get all the load cycles. Also, the fatigue loads used measured winds instead of synthetic winds, and measured SSME thrust instead of Main Propulsion Test Article (MPTA) thrust profiles.

Nominal Liftoff Fatigue Loads Cases

One hundred randomly nominally dispersed liftoff cases were created by using a "Monte Carlo" computer program to randomly assign values to the dispersions of those parameters that affect liftoff loads on the shuttle. Each parameter is taken as having either a normal or a random distribution. For each parameter, the mean and standard deviation (sigma) value are known. Then the computer program randomly assigns a value of from -4σ to $+4\sigma$ for each parameter with a probability distribution that is a normal distribution. (Note: very few values were over $\pm 3\sigma$.) Examples of these parameters are thrust mismatch between the right and left hand side boosters, SRB thrust misalignment, and time to 90% SSME thrust. The forcing functions representing SRB thrust are created from these parameters. Also the Monte Carlo program randomly selects from the available Orbiter models, SSME thrust measured profiles, and SSME measured sideloads for each mission.

Once the nominally dispersed cases are made, one design load case for each type of load is needed in the lifetime of one hundred missions. The design cases that are needed are identified by comparing the fatigue liftoff cases to the set of design liftoff cases, checking the body loads envelopes and the attach loads.

The body loads envelopes show the maximum and minimum load (three shears and three moments) at each node on the Orbiter fuselage and on the SRB. Where the fatigue body loads envelope fell significantly short of the design body loads envelope, additional fatigue cases were run to fill out the envelope. The attach loads were also compared for the component interfaces and the load indicators. Where the design certification load was 50% or more of the allowable load and the fatigue load was more than 20% below the design certification load, an additional fatigue case was considered necessary. Seven more cases were added by this criterion.

CONCLUSION

The result was that for both prelaunch and liftoff, a set of load cases with a good mix of nominal load cases, plus sufficient design load cases to ensure an occurrence of the design load for every component, were generated. This was achieved by:

1) Analysis of the program design certification requirements, as defined in Volume X.
2) Analysis of the shuttle missions to date
3) Checking of both the extrema and the distribution of the loads in the output loads cases and addition of cases to the database as needed.

LESSONS LEARNED

The experience of generating fatigue loads spectra for the space shuttle revealed a number of points which would be applicable to other programs and especially other reusable space vehicles.

1. Determine the analysis ground rules and assumptions as early as possible. (The tradeoff here is that it is often necessary to see some results before being able to decide whether assumptions are valid).

2. Plan to use tools and programs that are already in place for design loads analysis. But recognize that modifications will almost certainly be needed.

3. Plan for computer dataset storage. Fatigue files take up a great deal of space because 1) For fatigue, essentially the entire loads analysis is repeated, so there will be a full set of files for each flight segment; and 2) Fatigue files are often larger than their design counterparts; for example, fatigue liftoff datasets are larger than design liftoff datasets because they run for fourteen seconds instead of ten seconds.

    3a. Because of the enormous volume of data, it is vital to establish a consistent yet flexible naming convention for files before generating any data. Otherwise it may (will!) be impossible to find the data later.

    3b. Move files from on-line to tape storage continuously throughout the fatigue process as soon as they are not needed daily; don't wait until the end of the task. Waiting results in very high storage costs; a huge volume of dataset storage jobs at the end of the task; and a catalogue of files too large to navigate through.

4. Loads for the entire vehicle mission, including all flight segments, must be generated for fatigue. Generally for design there is a different system or tool for each flight segment because different forces are significant for each flight segment. Generally new loads cases must be generated for fatigue. The budget and schedule need to take account of the time to generate the cases of the cost of computer use and data storage, and of time to organize the information.

5. There are advantages to using a stress spectrum, rather than a loads spectrum, for fatigue/fracture analysis. A stress spectrum is less complicated than a loads spectrum because the loads spectrum must include time-consistent loads in all other degrees of freedom at the location, and sometimes at other locations as well, while a stress spectrum does not. Furthermore, in locations where the stress is strongly influenced by the loads in more than one of the principal directions, the peaks of the loads may not be peaks of stress.

In order to generate a stress spectrum, coefficients for converting load to stress must be provided by the stress group for each desired location. The coefficients are generated either by unit-load runs of finite-element models, or by hand calculation. Loads must be converted to stresses *before peak counting*, and the schedule for provision of these coefficients must reflect this.

6. Close coordination between fatigue loads personnel and stress personnel is essential from the beginning of the program in order to ensure that:

- All the necessary locations and types of spectra are identified from the start
- The spectra generated are what the stress analysts need to do their work
- There is complete understanding and agreement about what each spectrum represents
- Unnecessary spectra are not generated, saving time and money.

7. A strategy of continuous evolutionary improvement is well suited to the task of fatigue loads spectra generation. Under Rockwell's Continuous Improvement (ci) program, there were four or five meetings of the Fatigue Product Improvement Team specifically to scrutinize the fatigue loads spectra process and to seek places in the process that were inefficient, inadequate, or offered potential for problems. The meetings gave the team members a chance to step back from the "trees" and see the "forest". Ideas developed in the meetings resulted in improvements that dramatically cut the cost and time for the analysis. Particularly significant were the concept of a single, compressed "Universal Database" output format and the automation of several steps of the fatigue spectra process.

Not only did significant ideas come from the meetings, but they gave team members a start in the habit of constantly looking for areas that needed improvement and developing improvements.

8. Last, but far from least, the fatigue loads spectra were very much a team effort. Team members checked each other's results, assisted each other with computer programming, "bounced" ideas off each other, and generally increased the morale of the whole team. It is not exaggeration to say that this task could not have been performed without a team approach.

Table 1. Mission and Time on Launch Pad

Flt Seq	Mission	Orbiter OV-	Days on Pad	Days on pad for: OV-102	OV-103	OV-104	OV-099	Launch Date	On pad Date
1	STS-01	102	105	105				4/12/81	12/28/80
2	STS-02	102	74	74				11/12/81	8/30/81
3	STS-03	102	34	34				3/22/82	2/16/82
4	STS-04	102	33	33				7/27/82	6/24/82
5	STS-05	102	52	52				11/11/82	9/20/82
6	STS-06	099	126				126	4/4/83	11/29/82
7	STS-07	099	24				24	6/18/83	5/25/83
8	STS-08	099	29				29	8/30/83	8/1/83
9	STS-09	102	39	39				11/28/83	10/20/83
10	STS-11	099	22				22	2/3/84	1/12/84
11	STS-13	099	19				19	4/6/84	3/18/84
12	STS-14	103	78		78			8/30/84	6/13/84
13	STS-17	099	23				23	10/5/84	9/12/84
14	STS-19	103	17		17			11/8/84	10/22/84
15	STS-20	103	20		20			1/24/85	1/4/85
16	STS-23	103	14		14			4/12/85	3/29/85
17	STS-24	099	16				16	4/29/85	4/13/85
18	STS-25	103	15		15			6/17/85	6/2/85
19	STS-26	099	14				14	7/29/85	7/15/85
20	STS-27	103	31		31			8/27/85	7/27/85
21	STS-28	104	34			34		10/3/85	8/30/85
22	STS-30	099	15				15	10/30/85	10/15/85
23	STS-31	104	15			15		11/26/85	11/11/85
24	STS-32	102	42	42				1/12/86	12/1/85
25	STS-33	099	38				38	1/28/86	12/21/85
26	STS-26R	103	88		88			9/29/88	7/3/88
27	STS-27R	104	31			31		12/2/88	11/1/88
28	STS-29R	103	39		39			3/13/89	2/2/89
29	STS-30R	104	44			44		5/4/89	3/21/89
30	STS-28R	102	25	25				8/8/89	7/14/89
31	STS-34	104	51			51		10/18/89	8/28/89
32	STS-33R	103	27		27			11/22/89	10/26/89
33	STS-32R	102	43	43				1/9/90	11/27/89
34	STS-36	104	35			35		2/28/90	1/24/90
35	STS-31	103	39		39			4/24/90	3/16/90
36	STS-41	103	31		31			10/5/90	9/5/90
37	STS-38	104	75			75		11/15/90	2 TIMES
38	STS-35	102	161	161				12/2/90	2 TIMES
39	STS-39	103	49		49			4/28/91	2 TIMES
40	STS-37	104	22			22		4/5/91	3/15/91
41	STS-40	102	34	34				6/5/91	5/2/91
Total	(days)		1723	642	448	307	326		
Average	(days)		42.0	58.4	37.3	38.4	32.6		
Standard Dev			31.2						

42.024	0
42.024	18

Total Time on Pad = 1723 days
Average Time on Pad = 42.0 days
Standard Deviation = 31.2 Days for 41 Missions STS-1 through STS-40

Table 2. Time on Launch Pad for Each Mission and the Month in which it Occurred

Flt	Orbiter OV-	31 Jan	28 Feb	31 Mar	30 Apr	31 May	30 Jun	31 July	31 Aug	30 Sept	31 Oct	30 Nov	31 Dec	STS-
1	102	31	28	31	12								3	1
2	102								1	30	31	12		2
3	102		12	22										3
4	102						6	27						4
5	102									10	31	11		5
6	099	31	28	31	4							1	31	6
7	099					6	18							7
8	099								29					8
9	102										11	28		41A
10	099	19	3											41B
11	099			13	6									41C
12	103						17	31	30					41D
13	099									18	5			41G
14	103										9	8		51A
15	103	20												51C
16	103			2	12									51D
17	099				16									51B
18	103						15							51G
19	099							14						51F
20	103							4	27					51I
21	104								1	30	3			51J
22	099										15			61A
23	104											15		61B
24	102	12											30	61C
25	099	28											10	51L
26	103							28	31	29				26
27	104											29	2	27
28	103		26	13										29
29	104			10	30	4								30
30	102							17	8					28
31	104								3	30	18			34
32	103										5	22		33
33	102	9										3	31	32
34	104	7	28											36
35	103			15	24									31
36	103									25	6			41
37	104						13	31	8		7	16		38
38	102				9	31	11		22	30	26	30	2	35
39	103		15	7	27									39
40	104			17	5									37
41	102					29	5							40
Total		157	140	161	145	70	85	152	160	202	167	175	109	1723
		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Total
Percentage		9.1%	8.1%	9.3%	8.4%	4.1%	4.9%	8.8%	9.3%	11.7%	9.7%	10.2%	6.3%	
No. of flights that had shuttle on pad		8	7	10	10	4	7	7	10	8	12	11	7	101
		8%	7%	10%	10%	4%	7%	7%	10%	8%	12%	11%	7%	

Table 3. Probability of a Given Stay on the Launch Pad

Days	Probability of Exceedance of Stay	Midpoint (days)	Probability of Stay
12	1.00	21*	0.453
30	0.550	45	0.303
60	0.247	75	0.136
90	0.111	105	0.0613
120	0.0497	135	0.0274
150	0.0223	165	0.0123
180	0.0100	180 and up	0.0100

Table 4. Distribution of Length of Stay on Launch Pad for 100 Missions

Days on Pad	Number of missions
21	45
45	30
75	14
105	6
135	3
165	1
180	1

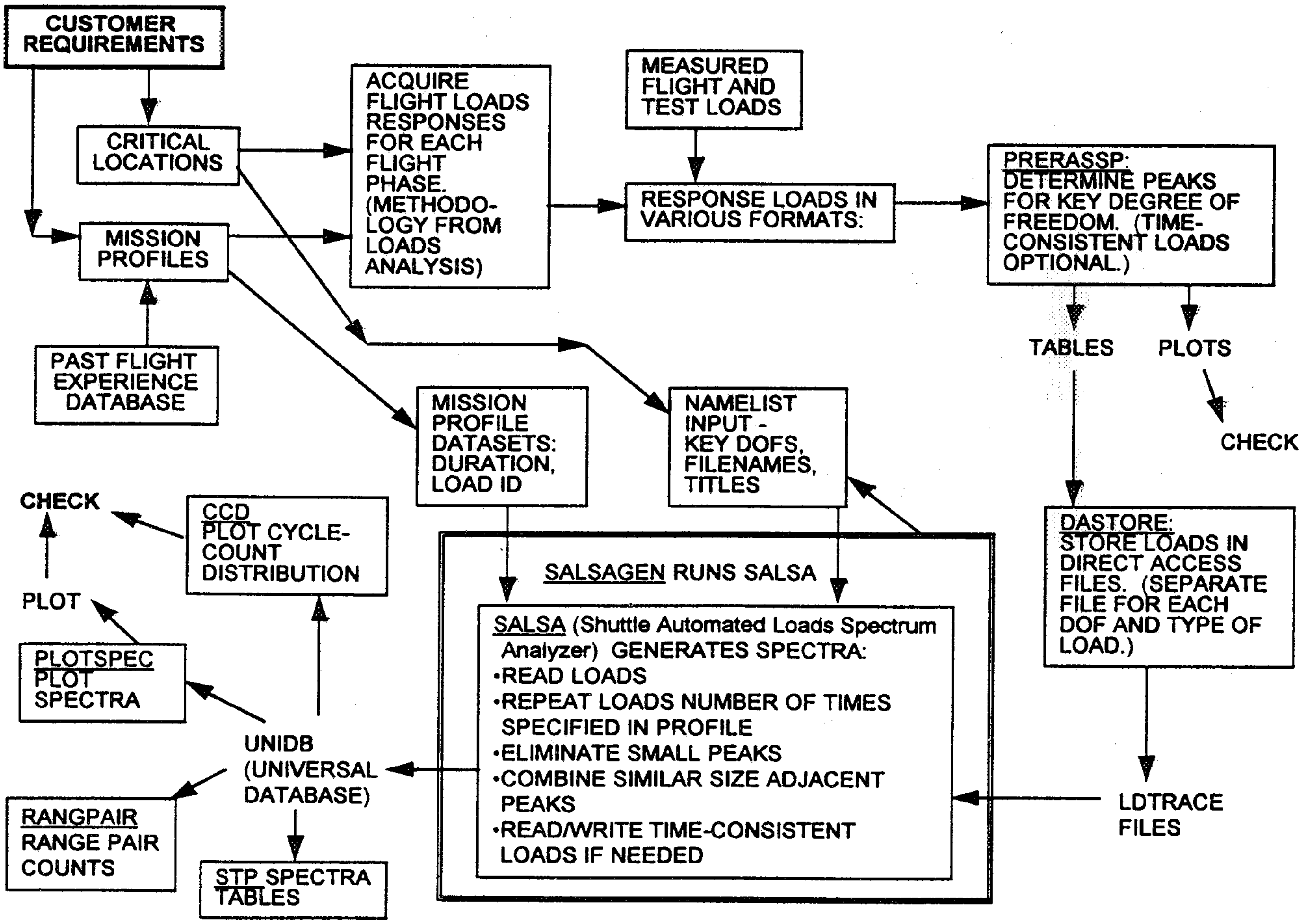


Figure 1. Fatigue Loads Spectra Process Flow

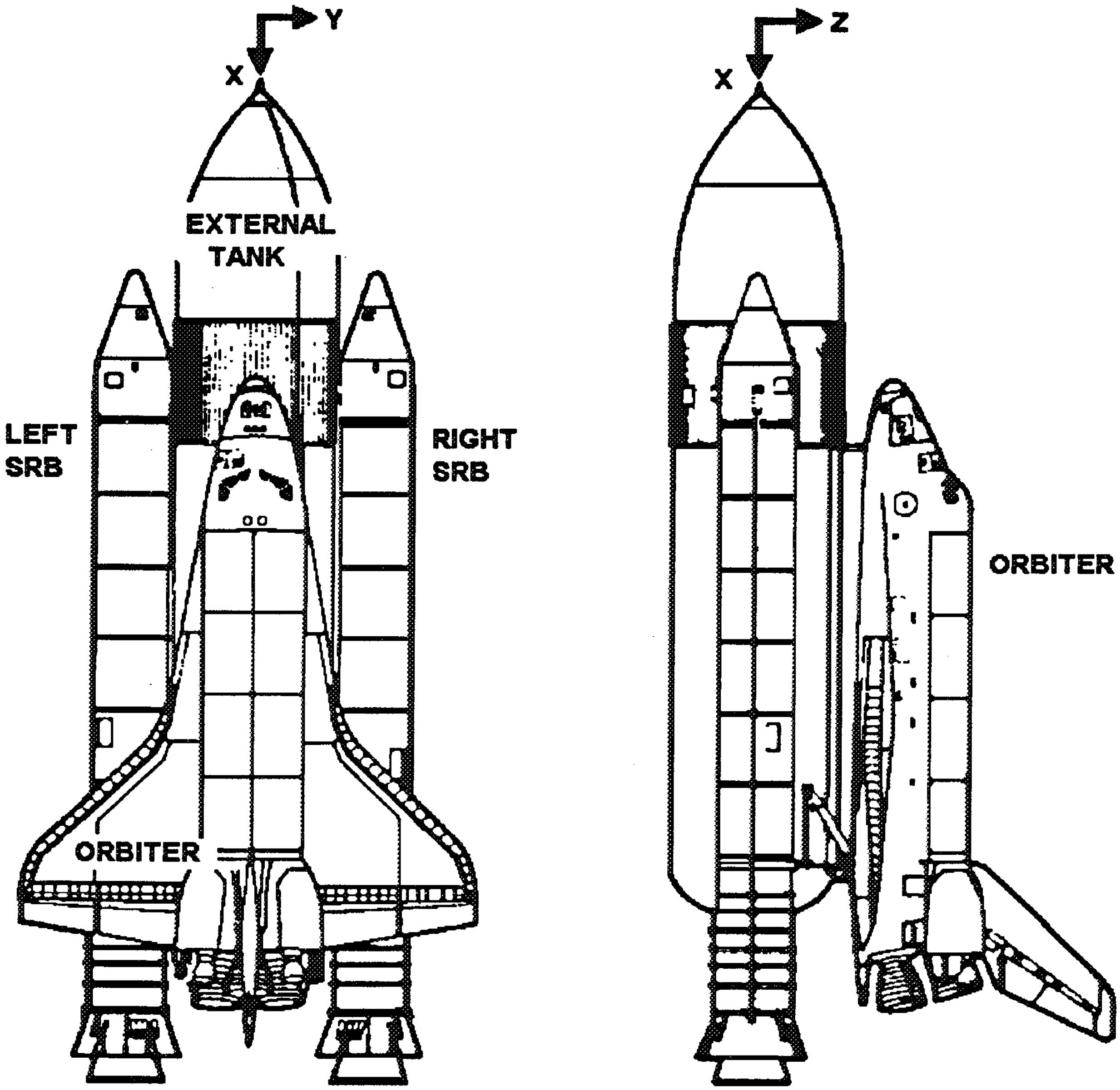


Figure 2. Launch Vehicle Geometry

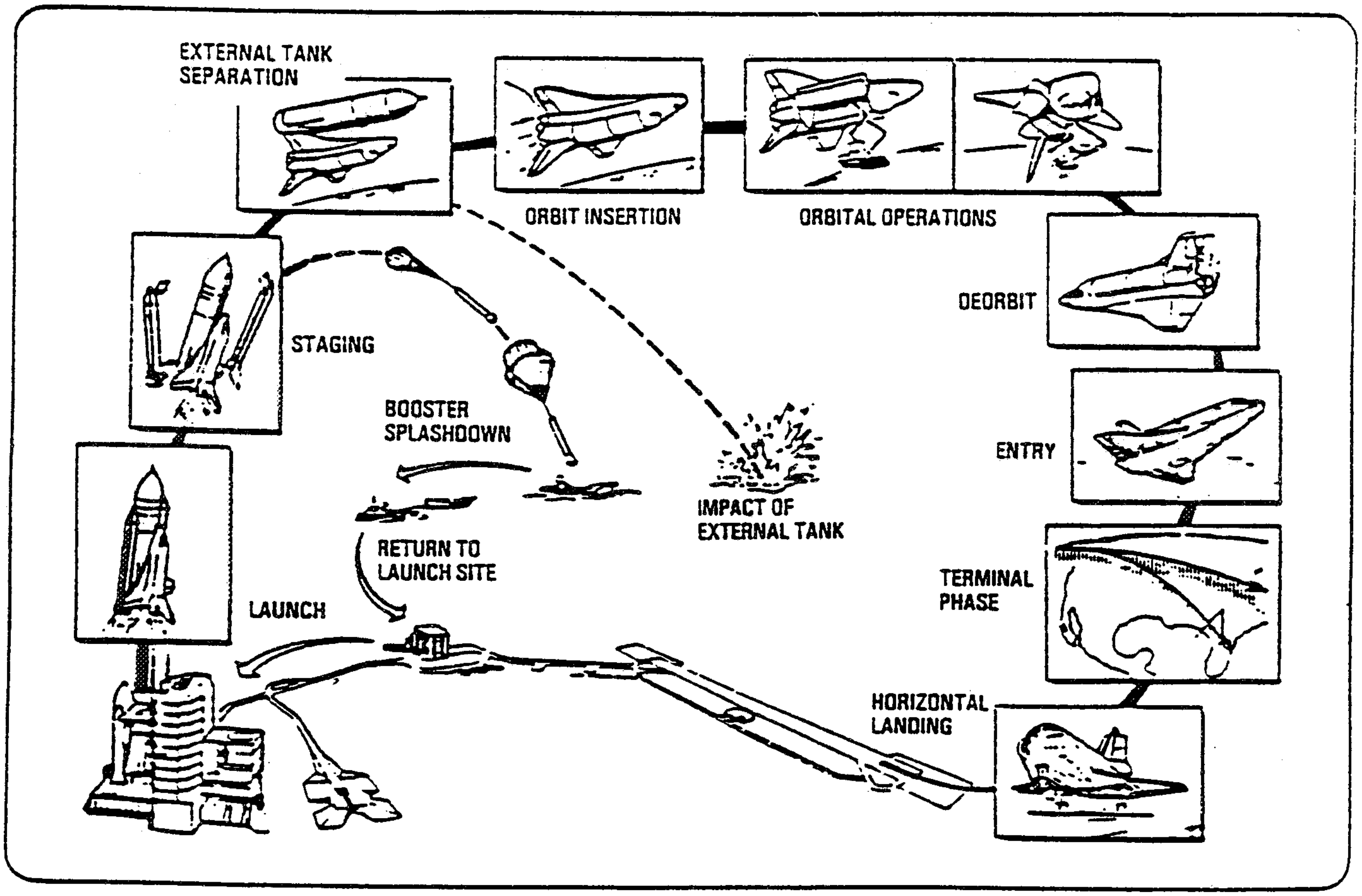


Figure 3. Space Shuttle Mission

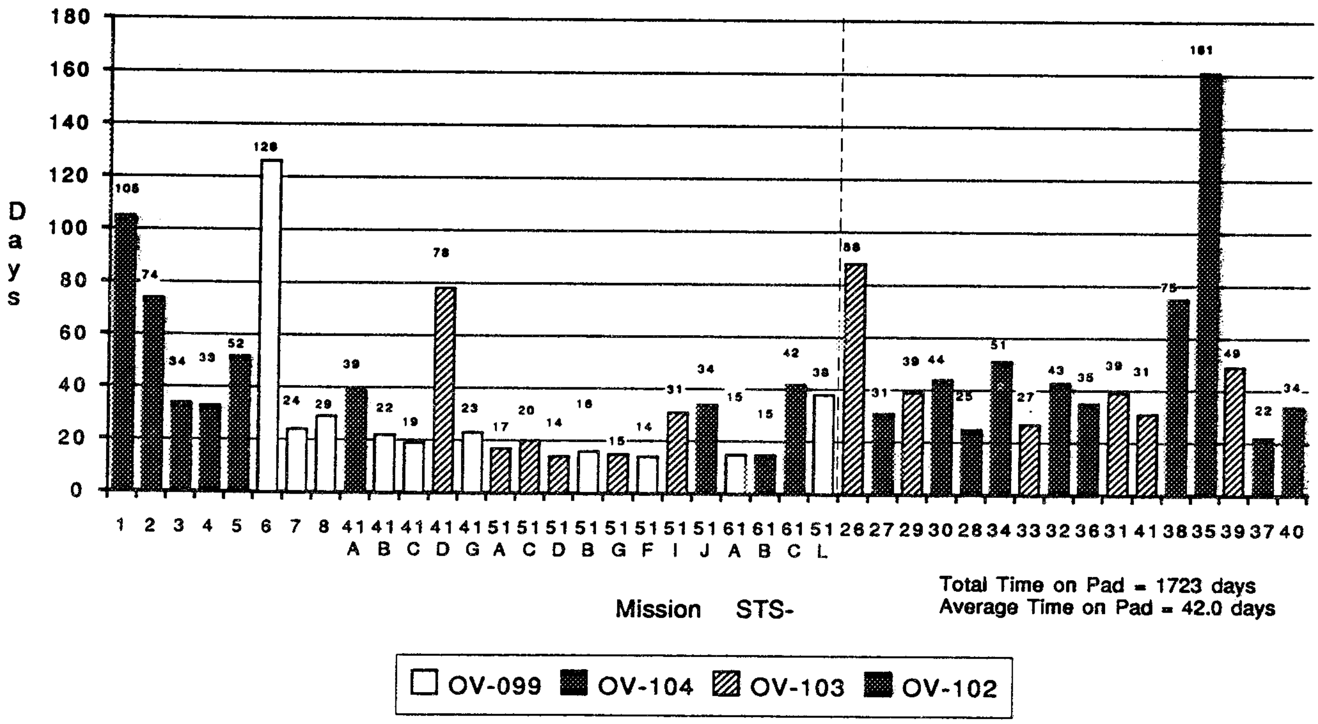


Figure 4. Time on Launch Pad for Each Mission

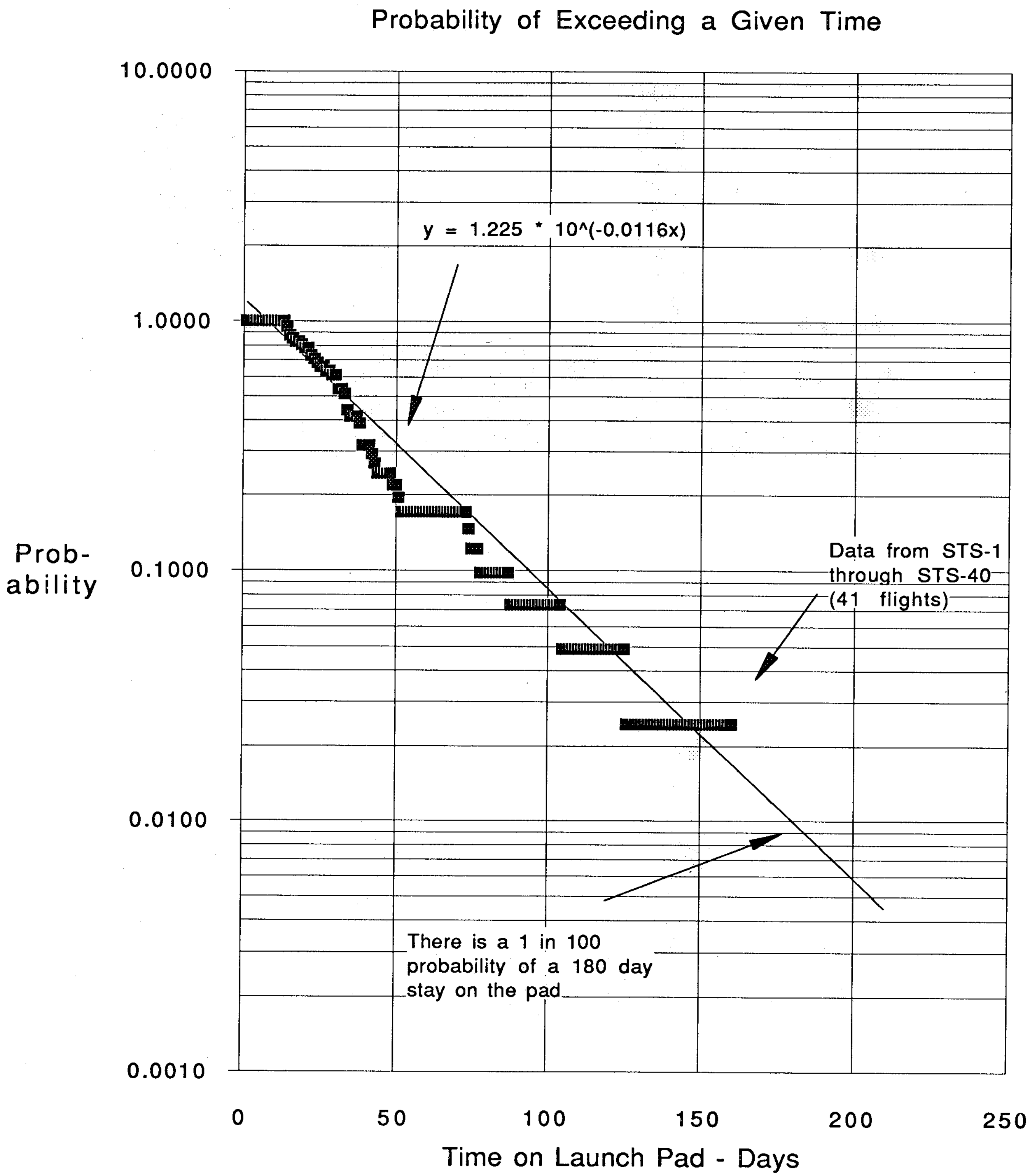


Figure 5. Time on Launch Pad

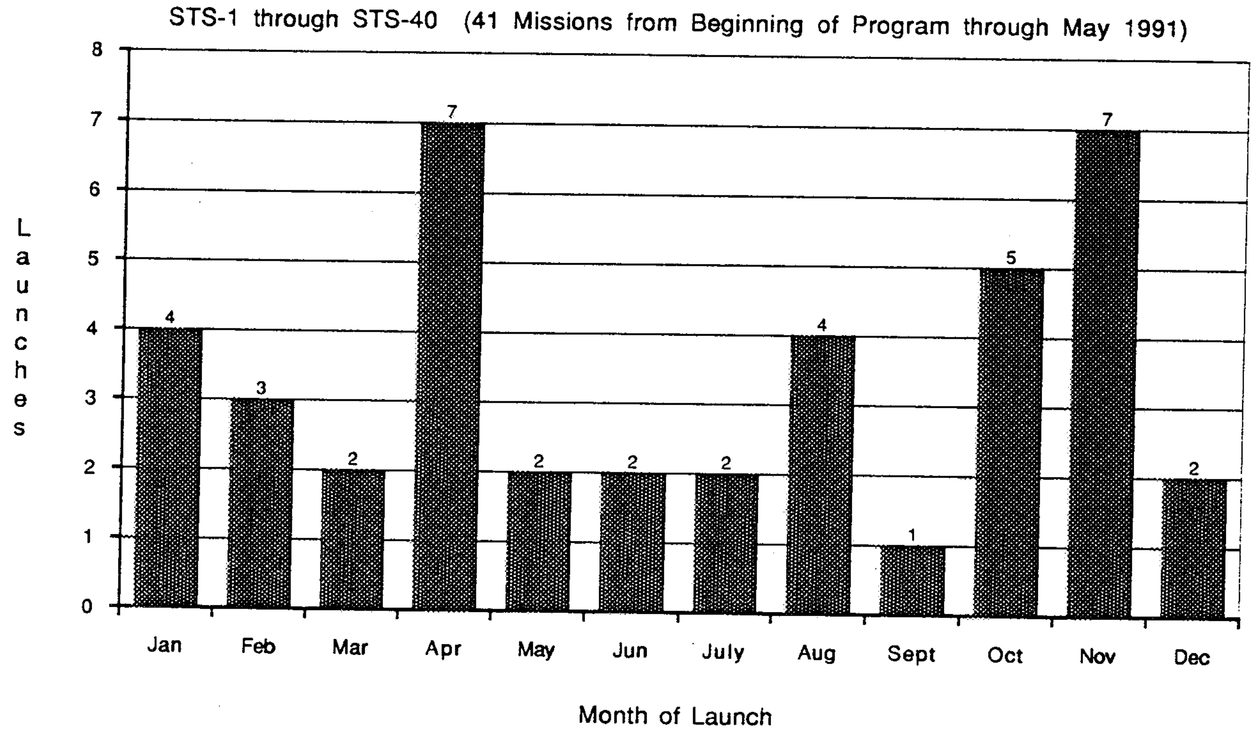
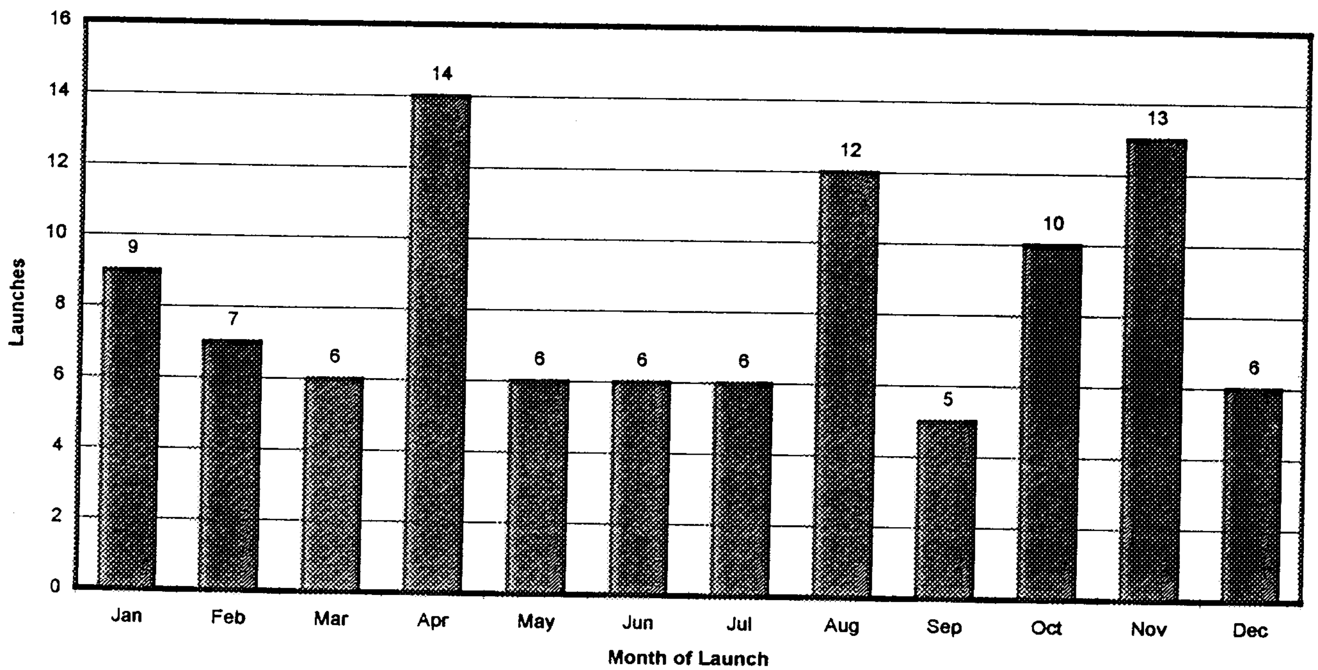


Figure 6. Number of Shuttle Launches in Each Month



Reference: (1) 41 Missions (STS-1 to STS-40)
(2) 3 Missions after (1) and 48 missions from flight manifest (1992-1997)
(3) 8 Missions projected based on (1) and (2)

Figure 7. Distribution of 100 Missions from KSC